

Design and Implementation of a high performance IPC for Intrusion Prevention using Socket API

Bachelor Thesis

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Abstract

Traditionally, host-based intrusion prevention systems utilize file-based logging as a means of Inter-process communication (IPC). However, a lack of bandwidth, or high latency, can unacceptably delay reception of critical information contained in these logs. This may lead to time-sensitive situations, for example a Denial-of-service (DoS) attack on the host system, escalating unnecessarily. Alternative IPC methods allow to remedy this issue. To this end, the light-weight prototype Simplefail2ban, based on Fail2ban, features a newly implemented IPC type utilizing shared memory, which has shown improved performance over file-based IPC.

Using Simplefail2ban, this thesis implements and evaluates another type of IPC based on UNIX domain sockets. It has been concluded that while this UNIX domain socket approach remains competitive under high loads of 30M unwanted Packets per second (PPS) stemming from up to 131,068 clients, the shared memory method outperforms this approach. When supplying multiple reader processes, the UNIX domain socket IPC lacks bandwidth and is unable to transmit messages at this rate. Still, at 20M PPS of unwanted traffic, the UNIX domain socket IPC type of Simplefail2ban is able to reliably defend against DoS attacks while providing log messages to multiple readers.

Deutsche Zusammenfassung

Traditionell verwenden Host-basierte Intrusion-Prevention-Systeme dateibasierte Lognachrichten zur Interprozesskommunikation. Mangelnde Bandbreite oder hohe Latenzen können jedoch den Empfang der in diesen Logs enthaltenen kritischen Informationen unannehmbar verzögern. Dies kann zeitkritische Situationen, wie zum Beispiel bei einem DoS-Angriff auf das Host-System, unnötig verschärfen. Alternative Interprozesskommunikationsmethoden können dieses Problem beheben. Dazu verfügt der auf Fail2ban basierende Leichtbau-Prototyp Simplefail2ban über einen neu implementierten Interprozesskommunikationstyp, der gemeinsam genutzten Speicher (Shared Memory) zweier Prozesse nutzt. Dieser Ansatz zeigt eine bessere Leistung als dateibasierte Interprozesskommunikation.

Diese Arbeit implementiert und evaluiert eine andere Art von Interprozesskommunikation auf Basis von UNIX Domain Sockets in Simplefail2ban. Es konnte festgestellt werden, dass diese Methode konkurrenzfähig ist, selbst unter hohen Lasten von 30 Millionen unerwünschten Paketen pro Sekunde von bis zu 131.068 Clients. Trotzdem bleibt der Shared-Memory-Ansatz performanter. Bei mehreren Leseprozessen fehlt es dem UNIX-Domain-Socket-Interprozesskommunikation an Bandbreite, um solche Lasten zuverlässig zu bewältigen. Dennoch gelingt es diesem Interprozesskommunikations-Typ von Simplefail2ban bei 20 Millionen Paketen pro Sekunde, DoS-Angriffe zuverlässig abzuwehren und gleichzeitig Lognachrichten an mehrere Leseprozesse zu liefern.

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1 Introduction

Development in internet infrastructure has led to higher interconnectedness over the course of the last century. Interacting with companies and governmental facilities is primarily done online. Deploying servers, providing specific services to the public, has become common place in daily life. With a continually growing importance of these servers, exploiting them becomes attractive for malicious actors. Identifying threats and security breaches is required to provide consistent uptime of servers. While traditional firewalls provide a starting point in defense against exploitation, they are not impenetrable. Common attacks, such as a Denial-of-service (DoS) attack, can circumvent these measures by imitating genuine clients. Draining system resources by sending illegitimate communication requests is simultaneously easy to do, and hard to protect against.

Additional monitoring of incoming traffic is done by Intrusion Detection Systems (IDSs). Interpreting a clients intent is done by analyzing system logs, as well as system and network resources. To actually combat incoming attacks, an Intrusion Prevention System (IPS) is required which actively defends system resources. A common industry standard for such an IPS is Fail2ban[1]. It scans a variety of information available on the host system, predominantly using log files as its source, technically making it a Host-based Intrusion Prevention System (HIPS). Clients deemed a threat to the host system are prohibited to interact with the host. Fail2ban achieves this by modifying the systems firewall.

However, previous work has shown that Fail2ban does not scale well when having to process a large number of log files instantaneously[2]. For networks with high bandwidth, a sudden influx in log messages can indicate an ongoing attack on the system. Fail2ban being unable to efficiently perform its duties in these heavy-load scenarios has serious downfalls. This inconsistent performance makes the system vulnerable against DoS attacks. It was determined that the intrinsic file-based logging approach of Fail2ban does not provide the necessary bandwidth or low latency required to repel DoS attacks successfully.

To remedy this issue a light-weight alternative to Fail2ban was developed: Simplefail2ban[3]. While inheriting the basic functionality of Fail2ban, this application provides the option to replace slow file-based logging with alternative Inter-process communication (IPC). During development, a shared memory IPC type was implemented. This allowed Simplefail2ban to outperform Fail2ban effortlessly[3], but if better alternatives exist remains unclear.

The main goal of this thesis is to design and implement an IPC mode based on UNIX domain sockets into Simplefail2ban in order to protect against DoS attacks. This includes an easily usable Application Programming Interface (API) and the option to attach multiple reader processes to the IPC architecture. In order to evaluate the performance of this socket IPC, a comparison with the already implemented shared memory and file IPC types is conducted.

Firstly, this thesis introduces background information regarding both Fail2ban and Sim-

plefail2ban. An explanation of the basic concepts used for the [IPC](#) is also included. Following that, a chapter is dedicated to introducing the design of the UNIX socket [IPC](#) architecture. A separate chapter will explain the intricacies of the implementation of said [IPC](#) type. In addition, the design of all experiments will be explained. To determine the performance of the socket [IPC](#), an extensive evaluation of the conducted measurements is included in this thesis. Finally, a summary of the findings of this thesis and a verdict on performance of both the shared memory and socket [IPC](#) type for Simplefail2ban is included.

2 Background & Motivation

This section establishes a definition for Host-based intrusion detection/prevention systems and introduces the example Fail2ban. An introduction to an alternative solution, Simple-fail2ban, and its necessity will also be discussed. Lastly, any external tools used in this thesis will also be discussed.

2.1 Host-based intrusion detection and prevention

Intrusion detection and prevention systems are tasked with monitoring the system and ensuring that no threat is present. While the former is only tasked with detecting on-going attacks, the latter actively defends system resources from exploits. The restriction to only utilize data available on the host system, differentiates a Host-based Intrusion Detection System (**HIDS**) from other forms of Intrusion Detection System (**IDS**). In general, collecting and analyzing data, identifying outliers, evaluating the risk these outliers pose, and responding to any potential threats or unusual behavior to minimize potential harm to the system, is the main task of an Intrusion Prevention System (**IPS**). According to James P. Anderson's study "Computer security threat monitoring and surveillance"[4] a threat is any deliberate attempt to either

- access data,
- manipulate data, or
- render a system unreliable or unusable.

With the ever-present risk of a system having a previously unknown vulnerability, proactive measures must be taken to prevent malicious actors' exploits. Real-time intrusion detection systems are required to achieve this goal. The motivation for such a system is outlined by Dorothy E. Denning[5]:

- The majority of systems have vulnerabilities, rendering them susceptible.
- Replacing systems with known vulnerabilities is difficult. Specific features may only be present in the less-secure system.
- Developing absolutely secure systems is difficult, since the explicit absence of vulnerabilities can rarely be proven.
- Secure systems remain vulnerable to insiders misusing their privileges.

For the purposes of this paper, defending against a Denial-of-service (**DoS**) attack, the basic assumption that any system is exploitable will suffice.

A **HIDS** generally collects data from multiple sources, freely provided by the host. Such auditing of data needs to be tamper-proof and non-bypassable. Low-level system calls,

often containing such data, are preferable to achieve this goal. The anomaly based approach allows an intrusion detection system to create profiles representing legitimate behavior of clients, users and applications. Using statistical tests on normal behavior of clients, any deviations are detected and interpreted as an attack on the system. This retains the advantage of not explicitly defining attack patterns, creating a more robust system which can identify new threats on its own.[6]

2.1.1 Fail2ban

Fail2ban is an open-source intrusion prevention system, developed in Python, running in the user space level. In contrast to an intrusion detection system, an **IPS**, such as Fail2ban, immediately takes deliberate measures once a threat has been identified to stop attacks on a system. By default, Fail2ban scans a variety of commonly used log files using Regular Expression (**Regex**), also called filters, to identify threats. It is therefore able to parse and monitor log data of a variety of different applications. A client will be identified as a threat if it repeatedly fails a certain task, for example establishing a Transmission Control Protocol (**TCP**) connection. Such a client is then banned by modifying the system firewall, adding its Internet Protocol (**IP**) address, to deny any further incoming traffic.[1]

In detail, Fail2ban creates so called jails. These jails are saved on persistent storage. Therefore, restarting Fail2ban or the machine running it will not result in a loss of current jail entries. A jail consists of a log path, a certain filter, an action and a variety of customizable parameters. The filter requires at least one **Regex** pattern. These patterns define what behavior Fail2ban should tolerate or not. An action, commonly a command or program, is to be executed once a client has been deemed a threat. Further parameters define the time the action will be active (ban time) and how often bad behavior of a client must be identified (ban limit) in log files to issue a ban. In practice, if a client fails to adhere to what the filter of a jail defines as proper behavior, vital information of that client is deduced by the analyzed log messages. This includes the **IP** address of the client. A ban will then be issued and a certain action, for example dropping all traffic with the source **IP** of the banned client, would be performed. To issue such a ban, temporary changes to the system firewall, using **iptables**, are performed. **iptables** allows user space programs, such as Fail2ban, to modify, add and remove rules for packet filtering. An incoming package has to pass each set of rules before reaching the destined application. Fail2ban creates a separate rule for each banned client via **iptables**. New incoming packets are checked against all rules defined by **iptables**, or until they infringe upon at least one rule. Especially when many clients need to be banned this exerts an ever-increasing load on the processing capabilities of the firewall, as each banned client corresponds to one additional rule future traffic has to be compared to.[2]

2.1.2 Extended Berkeley Packet Filter

The extended Berkeley Packet Filter (**eBPF**) provides the opportunity to run user-generated code in a privileged setting, such as the kernel. Such **eBPF** programs are written in high-level programming languages, for example C. Compilers convert these programs to **eBPF** bytecode in user space. Successfully deploying the code requires an **eBPF** verifier to accept

the program. This is done exclusively in kernel space as to limit risk to the security of the operating system. If the eBPF program is accepted, the program will be converted to eBPF native machine code. There are several hooks to which an eBPF program can be attached to. Depending on the chosen hook, the eBPF program is deployed in or even before the network stack. Meaning, the eBPF program receives incoming traffic while the operating system is still processing it in kernel space.[2]

In this thesis, the eXpress Data Path (XDP) Driver hook is used for all eBPF programs. Simply put, the eBPF program and its user-generated code is run before the kernel has performed its usual processing steps for incoming traffic. This way, the program will receive each incoming packet and can decide to let it pass to the kernel unhindered, or drop it at an early processing stage.

Since eBPF programs are event-driven, they only handle one packet at a time. In order to communicate with other programs or even store information, eBPF Maps are used. These maps are a key-value store and provide persistent storage. However, the size of eBPF maps needs to be defined before runtime, as it cannot be altered at a later stage.[2]

Using eBPF programs provides a significant advantage over the iptables approach of filtering packets. It is possible to drop unwanted packets before they reach the computation heavy kernel network stack, potentially saving resources on packets which ultimately would have been discarded anyway. And while eBPF programs have a variety of useful other applications, for purposes of this thesis, they are only used to either accept packets and pass them to the kernel or drop them to lighten workload.

2.1.3 Simplefail2ban

Florian Mikolajczak has shown[2] that Fail2ban performs poorly when dealing with large amounts of incoming unwanted traffic. This issue remains even after an alternative, and competitive, method of filtering incoming traffic using eBPF programs was implemented. To remedy this shortcoming, Simplefail2ban was developed[3]. It was suspected that Fail2ban is losing performance by exclusively utilizing traditional file-based logging. The goal was to implement an IPS that can prohibit malicious actors from sending traffic to the host system, similarly to Fail2ban, without having to rely on file-based logging.

Simplefail2ban provides the option to use a shared memory section to receive log messages. This significant change proved to be a faster method to transmit log messages from an application directly to Simplefail2ban. However, the general requirements for banning a client are unchanged. The IPS still monitors incoming log messages for disallowed behavior.¹ Each violation of the rules imposed by Simplefail2ban results in the clients IP being logged in a hashtable. If the number of entries for one IP address surpasses the defined ban limit, that client is banned via one of the banning threads of Simplefail2ban. This ban is facilitated by adding the IP address to a list of banned clients with the current timestamp, and an eBPF map. An eBPF program developed by Florian Mikolajczak will check if incoming traffic should either be dropped or passed along to the kernel, depending on the eBPF map entries[2]. The list of banned clients is routinely checked by the unbanning thread, removing clients whose ban time has elapsed from the hashtable, ban list and

¹Since Simplefail2ban is just a prototype, the distinction between allowed and disallowed behavior is based upon the payload of incoming traffic.

eBPF map, effectively re-allowing client interaction.[3].

2.2 Inter-process communication

While a variety of methods for inter-process communication exist, the nature of this thesis only necessitates the detailed comparison between the shared memory and socket approach. Therefore, understanding technical details of both Inter-process communication (IPC) types is vital to reach a conclusive verdict. Development was conducted on a Linux based system which will be reflected when discussing technical details.

2.2.1 Shared memory approach by Paul Raatschen

While Paul Raatschen initially considered multiple IPC types, such as shared memory, named pipes, sockets and message queues, only the shared memory approach was implemented as the most viable option. This was because it did not require any involvement of the kernel during write or read operations, and thus no context-switches between kernel- and user-space. Hence, if the synchronization overhead for the communication processes could be kept to a minimum, the IPC could operate almost at the speed of normal memory access. With no precursor on how to implement IPC based on shared memory, Paul Raatschen settled for an accumulation of independent segments. Each segment consists of a single ring buffer.[3]

Ring buffers are common array-like data structures. When saving data in a ring buffer, data is written in order into the buffer. For each data entry, the writer index position is incremented by one. Once the buffer is filled, the writer index loops back to the beginning of the array. Receiving data from a ring buffer works in a similar fashion. Once the end of the array is reached, the reader index is again set to the beginning of the ring buffer. Therefore, one can imagine the end of a ring buffer being connected with its first array element, resulting in a circular array. Overall, this results in data being read in a first-in first-out manner, with the index of the writing process preceding the index of the reading process. However, due to a multitude of reasons, the writer process might catch up to the index of the reader process. If this happens, there are two possible courses of action: Either wait for the reader index to move, and then write new data into the ring buffer; or overwrite the entry not yet read by the reader process. While overwriting the entry in the ring buffer leads to loss of data, the writer process is not slowed down by the reader process. Using shared memory, the desired approach can be defined by setting the option “overwrite” to accept data losses[3].

Segments are defined via a global header, dictating certain shared variables. This includes the number of ring buffers, the number of entries each ring buffer has and the size of each array element in byte. While other components exist in the global header, they all serve to synchronize writers and readers in one way or another and are not vital in understanding the general design of the shared memory IPC type; for more details, refer to [3].

Once the shared memory section has been established, multiple reader processes can attach one reading thread to each segment. Yet, per design, only one writing thread attaches to each segment. This one-to-one mapping ensures no further synchronization between

multiple writer threads is required. Sending and receiving data can now be performed by each thread individually according to the base principles of ring buffers outlined above.

2.2.2 UNIX Domain Sockets

In order to explain what a UNIX domain socket is, one must understand regular internet sockets. On a Linux system, a socket is a file descriptor referring to an endpoint for communication[7]. While a variety of socket types exist, the actual socket (or file descriptor representing a socket) does not change. Instead, the way data is transmitted via a particular socket defines the socket type. The most common types of sockets are stream and datagram sockets.

Stream sockets provide a reliable two-way connection between communication partners. Not only do they guarantee that any data sent is transmitted without errors, but they also do preserve the order in which the data was sent. This behavior is achieved by utilizing the **TCP**. [8]

The foundation of **TCP** is a three-way handshake in which participants negotiate the parameters required for the data exchange. Error checking is performed on all messages. If data is corrupted, the recipient can and will request retransmission of the same data. A number of additional factors contribute to the complexity of **TCP**. However, for this thesis, the knowledge that **TCP**'s reliability is achieved via the cooperation of all participating partners will suffice.

In contrast, datagram sockets, also called connectionless sockets, are considered unreliable, because it is based on the User Datagram Protocol (**UDP**), not **TCP**. **UDP** does not guarantee that data will arrive at its destination. Consequently, the reception of data in correct sequence cannot be guaranteed either. The lack of a reliable connection between communication partners, instead using a best-effort service, results in lower latency during data exchange. [8]

When a socket is only represented via a path name on a local system, it is called a UNIX domain socket (also known as **AF_UNIX**). Unlike stream or datagram sockets, UNIX domain sockets are used for local-only inter-process communication. Therefore, while they do inherit similar functionality as the internet sockets, they can shed slow communication protocols and provide faster communication. Data is never sent beyond system boundaries and only handled by the kernel. There are three socket types in the UNIX domain [9]:

- **SOCK_STREAM**: Stream-oriented socket (comparable to stream sockets), establishing connections and keeping them open until explicitly closed by one communication partner.
- **SOCK_DGRAM**: Datagram-oriented socket (comparable to datagram sockets), preserving message boundaries. In contrast to datagram sockets, **SOCK_DGRAM** is reliable and does not reorder sent data in most UNIX implementations.
- **SOCK_SEQPACKET**: Sequence-packet socket, is connection-oriented, preserves message boundaries, and retains the order in which data was sent.

In conclusion, UNIX domain sockets retain the flexibility provided by traditional internet sockets allowing for decreased latency, but at the cost of being bound to the local system.

2.3 Packet generator: TRex

TRex is an open source traffic generator developed by Cisco Systems, capable of generating both stateless and stateful traffic[10].

TRex is based on the Data Plane Development Kit (DPDK), which is a framework designed to increase packet processing speeds for a limited number of Central Processing Unit (CPU) architecture. The increase in performance is mainly attributed to the Poll Mode Drivers (PMDs), which bypass the kernel's network stack.[11]

Providing the ability to use multiple cores to generate traffic, TRex can send up to 200Gb/sec with hardware supported by the DPDK framework. Utilizing Scapy, a packet manipulation library written in Python[12], TRex is able to generate a customizable stream of traffic, allowing the user to modify any packet field.[10]

This feature will be used to modify the source IP of all generated packets, to simulate attacks involving a large number of clients.

The failure to achieve advertised traffic rates when using stateful traffic in certain scenarios was already observed by Paul Raatschen. When deploying Simplefail2ban, incoming traffic of banned clients is dropped by the IPS before reaching the network stack of the kernel. Therefore, no application receives any packets, and consequently, no reply is sent. This results in a loss of performance for TRex, as it expects an Acknowledgment (ACK) packet when sending a Synchronize/Acknowledge (TCP-SYN) packet.[3]

Therefore, in the scope of this thesis, TRex is used to generate UDP traffic only.

3 Design

The following chapter discusses the design of the socket Inter-process communication ([IPC](#)) for Simplefail2ban. While reasoning the choice of UNIX domain sockets, advantages and disadvantages are presented.

3.1 Reasoning for UNIX Domain Sockets

In order to make an informed decision on which [IPC](#) type is suited best, requirements need to be specified. Since the task at hand is to defend against Denial-of-service ([DoS](#)) attacks on the host system, the following aspects are considered[3]:

- **Low latency**

Responding quickly to incoming threats is key to successfully block incoming attacks. A quick transfer of data to the Intrusion Prevention System ([IPS](#)) facilitates faster banning of malicious attackers, before they can overwhelm the system. In general, low overhead is required to achieve these goals.

- **High bandwidth**

Considering that the host system is bombarded with millions of packets each second during an ongoing [DoS](#) attack, high bandwidth between processes using the [IPC](#) is crucial. To avoid bottlenecks between the writer and the [IPS](#), large amounts of data need to be transmissible at once instead of requiring separate transmissions.

- **Reliability**

Ensuring that no crucial log messages are lost due to unreliability is desirable. Repeatedly missing information about malicious clients delays the response time of the [IPS](#), risking uptime of the system and its services.

- **Scalability**

Log messages can come from a multitude of sources and contain a variety of information. Multiple applications should be able to submit log messages to the [IPS](#) at once, and retain the possibility of providing it to other applications. Therefore, the option to have both multiple readers and writers should be present. While not necessary for the development of a host-based [IPS](#), the option to scale beyond the local filesystem is interesting.

- **Portability**

Developing an [IPS](#) requires it to actually be usable with already existing applications. Whereas this thesis aims at presenting a fully functioning proof of concept, potential future development may still require some flexibility. A well-defined Application

Programming Interface ([API](#)) that can realistically be integrated into any application, without the need for specific hard- and software, greatly facilitates portability.

Initially, the decision by Paul Raatschen to utilize shared memory as the [IPC](#)[3]. No other [IPC](#) method was implemented. To ensure that the shared memory approach is the most viable, an alternative needed to be chosen to be measured against.

The choice fell on UNIX domain sockets, due to the already existing write and read [API](#) and its support in the Posix standard on all UNIX systems since at least 2007[13]. Additionally, the utilization of sockets provides a great deal of flexibility during usage of the [IPC](#). Since UNIX domain sockets are already an established mode of [IPC](#), it is suspected that they also provide the desired low latency and high bandwidth. Furthermore, they are reliable[9] and theoretically provide the opportunity to replace them with traditional internet sockets to scale beyond the local system.

3.2 Design and abstractions

During the design process of the socket architecture it was decided that supporting attachment of multiple readers was essential, as already discussed in section 3.1. Each reader should receive all log messages sent by any writers. These restrictions led to the design illustrated in figure 3.1.

This figure displays the general data flow using the socket [IPC](#) type. Each reader application creates its own UNIX domain socket. Sockets are bound to a filesystem pathname. Readers can receive data from their own socket without having to compete or synchronize with other readers for data thanks to the one-to-one mapping between socket and reader. Meanwhile, writers can also independently write data into sockets without having to communicate with other writer processes. In order to guarantee that readers receive all data being sent via the socket [IPC](#) architecture, writers need to periodically recheck for newly opened sockets and always send their data to all available sockets. This results in the writers having a significant portion of the overhead, needing to resend identical data multiple times. Minimizing overhead on the reader side is important to maximize the limited computational time that crucial services, such as the [IPS Simplefail2ban](#), have available to process incoming log messages.

To preserve the integrity of log messages, the UNIX domain socket needs to retain message boundaries, ruling out the `SOCK_STREAM` UNIX domain socket presented in section 2.2.2. Without the absolute guarantee of reliable behavior in regard to reordering of messages - only present in most UNIX implementations, but not all[9] - `SOCK_DGRAM` is unappealing as well. Therefore, the socket type choice falls on `SOCK_SEQPACKET`, a connection-oriented option that retains message-boundaries and sequence.

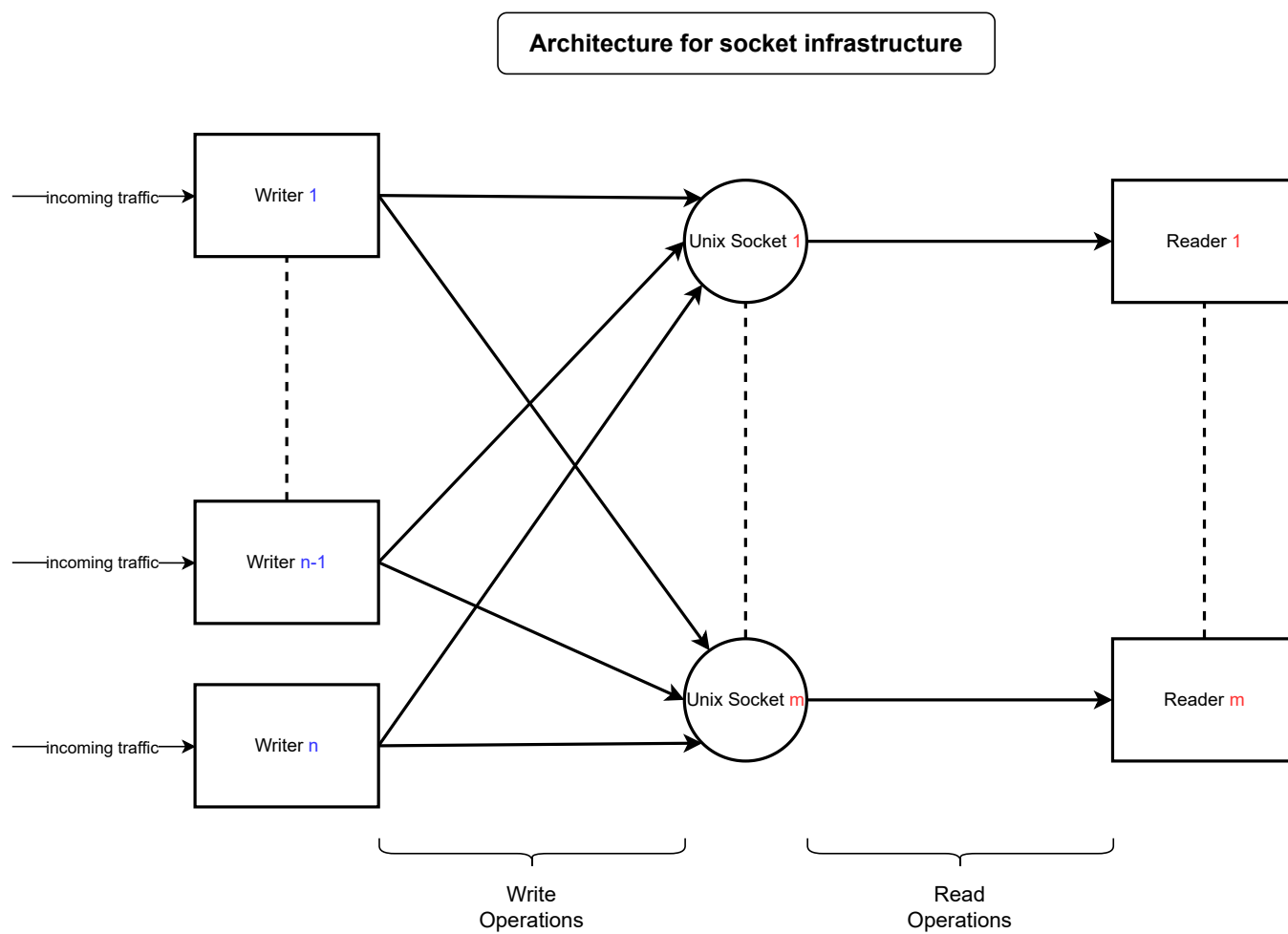


Figure 3.1: Architecture for a n -reader and m -writers scenario using UNIX domain sockets.

4 Implementation

In this chapter, the implementation of the previously discussed design (Reference: 3.2) for the UNIX domain socket architecture in the programming language C is presented. This includes an explanation of the write and read Application Programming Interface (API). All error codes are numeric and defined in the file `io_ipc.h`.

4.1 Auxiliary functions and structures

When utilizing the socket Inter-process communication (IPC) type, some shared resources seen in 4.1 need to be set up. None of these are modifiable during runtime.

```
1 #define MAX_AMOUNT_OF_SOCKETS 32
2
3 // This has to be long enough to fit the number or the socket
  and a terminating null byte
4 #define SOCKET_TEMPLATE_LENGTH 128
5 #define SOCKET_NAME_TEMPLATE "/tmp/unixDomainSock4SF2B_"
```

Algorithm 4.1: Parameters shared between readers and writers.

To ensure that no writer gets stuck continually checking for an infinite amount of new sockets, the global variable `MAX_AMOUNT_OF_SOCKETS` is defined as an upper limit. A special feature of the socket IPC type is the possibility of attaching a variable number of reader and writer processes, even during runtime. In fact, there is no actual limit for attaching new writer processes. Meanwhile, only up to `MAX_AMOUNT_OF_SOCKETS` reader processes can exist because of the strict one-to-one mapping between readers and sockets.

All UNIX domain sockets were bound to the filesystem, resulting in a common path to the location of all sockets needing to be supplied to both readers and writers. However, this `SOCKET_NAME_TEMPLATE` is not the full path to each socket. During runtime, each reader process trying to attach will append this name template with their own reader Identification (ID). The reader ID is determined by claiming the first ID not already in use. Since the length of the reader ID being appended to the `SOCKET_NAME_TEMPLATE` can vary, a length for this template is defined in `SOCKET_TEMPLATE_LENGTH`. It should be defined in such a manner, that both the appended reader ID and a terminating null byte can be appended to `SOCKET_NAME_TEMPLATE`.

Separating functions utilized by readers and writers results in an unwieldy API. Shared usage of functions by both sides is achieved by supplying function calls with the role of the calling process, either `SOCK_WRITER` or `SOCK_READER`.

```
1 int sock_init(union sock_arg_t *sock_args,
2               int role);
```

Algorithm 4.2: Initialization function for both reader and writer processes.

Therefore the function initializing communication between processes, `sock_init` as per 4.2 only requires a structure of parameters and the role of the calling process. Defining a union containing both writer and reader structures, as seen in 4.3, allows the user of the API to provide either one as a parameter for the same function. The actual purpose of `sock_init` is to enable connection between writer and readers by initiating the associated structure passed in the parameter `sock_args`. An explanation of both the `sock_writer_arg_t` and `sock_reader_arg_t` will follow in the next sections 4.2 and 4.3. Writers are provided with a list of possible locations of UNIX domain sockets belonging to reader processes. Meanwhile, readers are assigned a path, in which they create a UNIX domain socket. This path has to conform with `SOCKET_NAME_TEMPLATE` as outlined above. All sockets are set to be of the type `SOCK_SEQPACKET`.

```
1 union sock_arg_t{
2     struct sock_writer_arg_t wargs;
3     struct sock_reader_arg_t rargs;
4 };
```

Algorithm 4.3: Union containing either the parameters of a writer or reader process.

While other IPC types such as shared memory required an orderly detachment of writers and readers, this is not necessary for the socket approach. Instead, when terminating a reader process, only closure of the corresponding UNIX domain socket is necessary. Currently, stopping a writer process results in deconstructing the entire UNIX domain socket architecture. This results in the functions `socket_finalize` and `socket_cleanup`, as shown in 4.4 and 4.5 respectively, being identical in behavior. In fact, `socket_finalize` simply calls `socket_cleanup` and was only provided in the socket API to make a seamless replacement of other finalize-style functions when switching IPC types possible.

```
1 int sock_finalize(union sock_arg_t *sock_args, int role);
```

Algorithm 4.4: Cleanup initialization function of socket IPC.

```
1 int sock_cleanup(union sock_arg_t *sock_args, int role);
```

Algorithm 4.5: Cleanup of socket IPC.

4.2 Write API

The write API consists of a single, versatile function to transmit a variable number of messages: `sock_writev`. See algorithm 4.6 for its definition.

It requires four arguments:

- A pointer to an instance of the structure `sock_writer_arg_t` which will be introduced shortly.
- A pointer to an array of `iovec` structures. Each `iovec` structure defines separate memory regions of a variable size, acting as a buffer. An entire array of such structures represent a vector of memory regions[14].
- The integer `invalid_count` represents the number of log messages located in the `iovec` array. Each entry represents an attempt to establish an unwanted connection request from a malicious client.
- Finally, the maximum number of receiving sockets is given via the parameter `maxNumOfSocks` and is usually equal to `MAX_AMOUNT_OF_SOCKETS`. Setting `maxNumOfSocks` to a value smaller than `MAX_AMOUNT_OF_SOCKETS` results in that writer process only supplying a subset of sockets/readers with data.

```
1 int sock_writev(struct sock_writer_arg_t *sock_args ,
2               struct iovec *log_iovs ,
3               uint16_t invalid_count ,
4               uint16_t maxNumOfSocks);
```

Algorithm 4.6: Write API for the UNIX domain socket architecture

The structure `sock_writer_arg_t` contains all information needed by the writer process, as seen in 4.7.

```
1 struct sock_writer_arg_t
2 {
3     char socketPathNames[MAX_AMOUNT_OF_SOCKETS][
4         SOCKET_TEMPLATE_LENGTH];
5     struct sockaddr_un socketConnections[
6         SOCKET_TEMPLATE_LENGTH];
7     int socketRecvS[MAX_AMOUNT_OF_SOCKETS];
8     int writeSockets[MAX_AMOUNT_OF_SOCKETS];
9 };
```

Algorithm 4.7: Writer structure containing critical information being reused over several calls of `sock_writev`

The first parameter `socketPathNames` is an array containing all possible paths in which UNIX domain sockets could be located. Here, the necessity for defining the variables `MAX_AMOUNT_OF_SOCKETS` and `SOCKET_TEMPLATE_LENGTH` becomes evident. The entirety of the socket IPC is implemented as a static library. Consequently, arrays cannot be assigned a variable length during runtime. Another array, `socketConnections`, contains a collection of `sockaddr_un` structures. Each of these represents a single UNIX domain socket and their address information. The array `socketRecvs` stores integers displaying which sockets have already been connected to. Sockets can either be marked as not available (-1), available but not connected yet (0), or available and connected with the writer process (1). Lastly, `clientSockets` holds a collection of file descriptors referring to each connected socket, as created by the function `socket`.

When calling `sock_writev`, the first thing being performed is a check for newly available UNIX domain sockets. This can be considered analogous to checking for new readers because of the strict one-to-one mapping between sockets and readers. If new sockets were identified, a connection with that socket is established and saved for future calls of this function. Then, all sockets with an existing connection are sent the data located in the `iovec` structures using the blocking function `write`. On success, the function returns the number of sent messages via the socket IPC.

4.3 Read API

The function `sock_readv` is responsible for reading all available data out of the UNIX domain socket infrastructure. As seen in 4.8, the function takes two arguments.

```
1 int sock_readv(struct sock_reader_arg_t *sock_args ,
2               struct iovec *iovecs);
```

Algorithm 4.8: Read API for the UNIX domain socket architecture

The parameter `iovecs` is a pointer to an array of `iovec` structures. Any log messages received via the socket IPC are stored here for the calling reader process to access later. A structure containing all relevant information regarding the specific UNIX domain socket associated with the reader process is stored in `sock_args`. This structure, `sock_reader_arg_t`, is defined in 4.9.

Analogous to `sock_writer_arg_t`, the path of the socket assigned to the reader process is passed in `socketPathName`. Parameter `address` contains the structure `sockaddr_un` representing that same UNIX domain socket. Not wanting to redetermine the static size of the `address` for each function call, `sizeofAddressStruct` is passed along containing that exact value. Therefore, the size of `address` has to be determined only once during initializing communication, saving computational time. The integer `readSocket` contains the file descriptor referring to the readers UNIX domain socket, as created by the function `socket`. Saving already established connections with writer processes for future function calls is done in the array `clientSockets`.

```
1 struct sock_reader_arg_t
2 {
3     char socketPathName[SOCKET_TEMPLATE_LENGTH];
4     struct sockaddr_un address;
5     int sizeOfAddressStruct;
6     int readSocket;
7     int clientSockets[MAX_AMOUNT_OF_SOCKETS];
8 };
```

Algorithm 4.9: Reader structure containing critical information being reused over several calls of `sock_readv`

Calling `sock_readv` creates a list of clients which the blocking function `select` will regularly poll.

`select` waits for at least one file descriptor (analogous to: UNIX domain socket) to become ready for an I/O operation. A file descriptor is considered ready once a call of `read` or `write` will not block if performed.[15]

This stops the function `sock_readv` having to either be stuck in a blocking call of `read`, or return from a non-blocking call of `read` with an error code. Having a blocking call of `select` instead of `read` is desirable because it allows `sock_readv` to accept connections of new writer processes while waiting for data to arrive. Once `select` returns, `sock_readv` checks if new connections need to be accepted. If not, one of the already connected writer processes has sent data via the UNIX domain socket, which is ready to be read. All received data is then saved in the provided parameter `iovecs`, allowing the calling process of `sock_readv` to access it. The function `sock_readv` will then terminate and return the number of received messages.

5 Experiments

Paul Raatschen has performed a study[3] concluding that the original Fail2ban process can be improved upon. It was determined that especially with many clients, Fail2ban struggled to keep up with high incoming traffic rates. To remedy this issue, a more performant program, Simplefail2ban, was implemented and measured. An increase in performance was evident. Simplefail2ban supported two modes of Inter-process communication (IPC). The file mode was akin to traditional file logging, while the shared memory approach would use a shared memory section to exchange data between processes. A direct comparison between the already outlined socket approach and previously supported IPC types necessitates the measurements in this chapter.

The following chapter details the measurements performed, outlining specifics according to Jain’s “The Art of Computer Systems Performance Analysis: Techniques For Experimental Design, Measurement, Simulation, and Modeling, NY: Wiley”[16] chapter 2.2.

5.1 Test environment

Two machines, both identical in hardware and software, were used in these experiments. The first machine, the Device under Test (DUT), ran Simplefail2ban and a test application responsible for receiving incoming traffic and reporting clients. The second machine generated and sent traffic, consisting of both valid and invalid traffic, to the DUT using TRex.

Table 5.1: Table of Hardware and Software parameters of the testbed. The first machine serves as the DUT. The second machine generates traffic to be sent to the DUT via TRex.

| Hardware | |
|------------|---------------------------------------------------------------------------|
| CPU | 16 × Intel(R) Xeon(R) Silver 4314 Central Processing Unit (CPU) @ 2.40GHz |
| NIC | Mellanox Technologies MT2892 Family [ConnectX-6 Dx] |
| RAM | 128 GB |
| Software | |
| OS | Debian GNU’s Not Unix (GNU)/Linux 11 |
| Kernel | 5.10.0-28-amd64 x86_64 |
| NIC Driver | mlx5_core; Version 5.8-2.0.3 |
| TRex | 2.99 (Stateless) |

5.2 Experimental design

In his thesis[3], Paul Raatschen showed that the shared memory mode of Simplefail2ban outperforms the traditional Fail2ban. However, it remains unclear if the implementation of this [IPC](#) type is more performant than other alternatives. Specifically, the possibility of using UNIX domain sockets as a mode of inter-process communication was not explored. The following experiments enable a direct comparison between the two [IPC](#) types.

In general, the experiments consist of two participants and a one-sided data exchange. The [DUT](#), or more specifically the application `udp_server`, receives a stream of both wanted and unwanted data. Identifying desired traffic is done by analyzing the message payload. This is a crude and unrealistic approach to filtering malicious communication requests. Such a simplification allows the application `udp_server` to quickly generate log messages. Since the goal of this study is to determine the most efficient [IPC](#) type for Simplefail2ban, it is very plausible that this abstraction does not diminish the findings of this thesis. To compare the differing [IPC](#) types, a set of performance metrics needs to be established:

Performance metrics

- Total number of unwanted requests dropped (number of packets)
- Total number of unwanted requests dropped, relative to the total amount of unwanted requests sent (percentage)
- Number of log messages processed by Simplefail2ban, relative to the number of log messages sent by the test server (percentage)
- [CPU](#) utilization of Simplefail2ban (seconds of [CPU](#) time)

Higher is better for the first three metrics. The last metric should be minimized for the [DUT](#) so its services are continually provided to valid clients.

The fixed parameters for each of the experiments are the following:

Fixed parameters

- Hardware and Software parameters of the testbed in this table:
 - [CPU](#): 16 cores, no hyper-threading enabled
 - Network Interface Card ([NIC](#)): Maximum transfer unit is 1500 bytes
 - [TRex](#): One interface, 30 threads
- Number of entries in extended Berkeley Packet Filter ([eBPF](#)) maps for IPv4 & IPv6: 1M
- Number of receiving threads used by `udp_server`: 16
- Duration of measurement: 300 Seconds
- Amount of valid traffic sent: 50,000 Packets per second ([PPS](#))

- Number of clients sending valid traffic: 254
- **Simplefail2ban** parameters:
 - Number of hash table bins used: 6,000,011
 - Ban threshold for clients: 3
 - Ban time for clients: 30 seconds
 - Enabling the Regular Expression ([Regex](#)) Matching feature of Simplefail2ban (the current implementation does not ban clients correctly when disabled)
 - For **shared memory** specifically:
 - * Number of banning threads used: 16
 - * Line count for the shared memory buffer segments: 1,000,000
 - * Segment count for the shared memory buffer: 16
 - * Overwrite feature enabled
 - * Workload stealing feature disabled
 - For **sockets** specifically:
 - * Number of banning threads used: 16
 - * Number of sockets: Same as number of reader processes (either one, or two when utilizing a second reader)
 - * Using default path to sockets created by the application: `tmp/`
 - * Using default socket receive and send buffer size configured on the system: 212,992 Bytes
 - For **file** specifically:
 - * Number of banning threads used: 1 (file mode only supports one banning threads)
 - * Buffer size for `uring_getlines`: 2048

The factors, or variable parameters, during these experiments were the following:

Factors and their levels

- Internet Protocol ([IP](#)) stack: IPv4, IPv6 and IPv4/IPv6 mixed
- Effects of differing amount of invalid traffic sent: 100k, 1M, 10M, 20M, 30M [PPS](#)
- Effects of differing number of clients sending invalid data: 65,534 and 131,068
 - Range used for 65,534 clients: 10.4.0.1 to 10.4.255.254 resulting in clients stemming from 256 subnets (using `offset_fixup` of 5 for IPv6 in TRex script).
 - Range used for 131,068 clients: 10.4.0.1 to 10.5.255.252 resulting in clients stemming from 512 subnets (using `offset_fixup` of 5 for IPv6 in TRex script).

- When using the IPv4/IPv6 IP stack, the range for 65,534 client is being used twice to generate both a IPv4 and IPv6 stream.
- Differing IPC type: FILE (traditional file-based logging), SHM (using shared memory), SOCK (using UNIX domain sockets)
- For shared memory specifically:
 - No 2nd Reader/ Enabling 2nd Reader
- For sockets specifically:
 - No 2nd Reader/ Enabling 2nd Reader

To generate the traffic being sent to the DUT, TRex scripts are used. These scripts provide the option to modify the sent traffic according to the factors outlined above. During these measurements, adapted versions of Paul Raatschens[3] scripts were used. To measure most performance metrics, an adaptation of the `xdp_ddos01_blacklist_cmdline` program was used. This application originally stems from Florian Mikolajczak master's thesis[2] and routinely polls the number of dropped and passed packets from a specific eBPF map. It was modified by Paul Raatschen to output values as a comma-separated values (CSV) file. The polled eBPF map is ultimately used by Simplefail2ban to ban clients. CPU time was measured via the command `top`.

5.3 Established Simplefail2ban IPC types

Software version changes warrant remeasurement of the shared memory and file IPC mode for Simplefail2ban. These will also be used to evaluate the newly implemented socket mode.

5.3.1 Experiment 1a: Simplefail2ban Logfile

It has already been shown that the file IPC type of Simplefail2ban is outperformed by the shared memory mode. Pure IPv4, IPv6 and a mixed IPv4/IPv6 IP stack will be used. File logging is expected to perform worse than the other IPC types discussed in this thesis, and acts as a baseline for the other IPC types. In total, 25 unique measurements were conducted for this experiment.

5.3.2 Experiment 1b: Simplefail2ban Shared Memory

The newly implemented socket approach is intended to be a valid alternative to the shared memory mode of Simplefail2ban. To enable a direct comparison, measurements for the shared memory mode need to be done under high enough loads, since with lower loads both the socket and shared memory mode are suspected to be performant enough. All levels of invalid traffic rates are measured individually. Again, either a pure IPv4, IPv6 or mixed IPv4/IPv6 IP stack is utilized. The most performant features will be used, meaning overwrite is enabled and workload stealing is disabled. No second reader process is being employed here. In total, 25 unique measurements were conducted for this experiment

5.4 Measuring the socket Application Programming Interface (API)

In the following section, thorough variations of factors and their levels are used to evaluate the performance of the socket mode. Also, heavy workloads are employed to determine how the socket mode performs in worst case scenarios. This will allow for a direct comparison between socket and shared memory mode. The data flow in the DUT can be seen in 5.1.

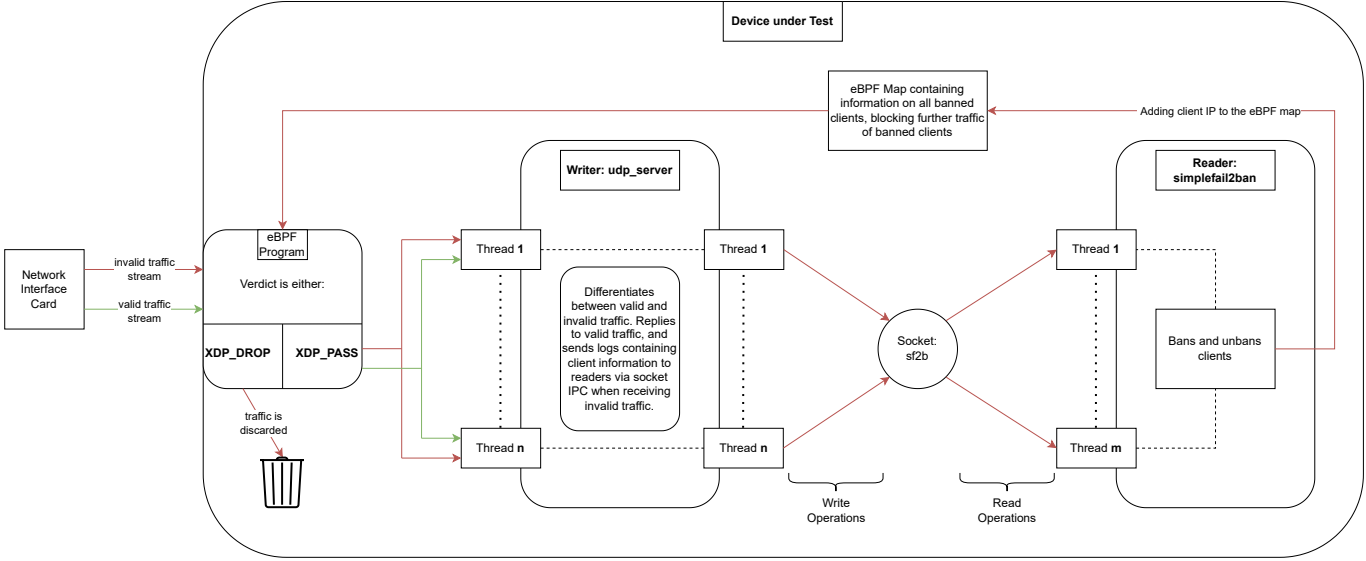


Figure 5.1: displays the data flow (left to right) on the DUT when enabling sockets as the IPC type. A packet can either be passed (XDP_PASS) to the kernel or dropped (XDP_DROP) before ever reaching the kernel.

5.4.1 Experiment 2: Simplefail2ban Sockets

To establish a baseline for the performance of the socket mode, all factors are set to all possible levels in every combination. The only exception being the possibility of using a second reader process, which will have its own section later. In total, 25 unique measurements were conducted for this experiment.

5.4.2 Experiment 3a: Replication of Simplefail2ban Shared Memory with 2nd Reader

In order to later compare the socket mode and its option to have a second reader, a baseline measurement needs to be established. This experiment will be performed with 131,068 clients sending invalid data only and no pure IPv4 or IPv6 IP stack. Again, the overwrite feature is enabled while workload stealing is disabled. The second reader process logs all messages it receives in a log file. In total, 5 unique measurements were conducted for this experiment.

5.4.3 Experiment 3b: Simplefail2ban Sockets with 2nd Reader

This experiment closely mirrors the experiment 3a. A total of 131,068 clients will send invalid data to the **DUT** with no pure IPv4 or IPv6 **IP** stack. The shared memory mode inherently supports the possibility of adding a second reader to the shared memory section to read log messages. There is no such inherent support in the socket mode. Instead in its current implementation, another read process can be started which will then be assigned its own socket. This socket will then also receive all log messages. Consequently, the shared memory mode will likely see a smaller performance loss, since no additional effort is required to send messages to the second reader. The second reader process logs all messages it receives in a log file. In total, 5 unique measurements were conducted for this experiment.

5.5 Evaluation of Experiments

The aforementioned experiments can be logically grouped into two categories: Baseline measurements and utilization of a second reader. Baseline measurements are conducted in experiments 1a, 1b and 2, second reader experiments in 3a and 3b. With 85 performed experiments, a thorough yet not unreasonably long evaluation of each measurement is infeasible. Instead, only especially expressive data will be covered in this section, with any notable or diverging observations being explicitly mentioned. For full measurement data on all experiments, refer to the repository provided in the sources[17].

Meaning of data variables

In the following section, each graph will be accompanied by an additional table. This table contains data that is not explicitly expressed otherwise. A total of six lines are plotted, with two of them belonging to each **IPC** type. For each **IPC** type (File, Shm, Sock), the total number of packets dropped by the **eBPF** program is denominated via **XDP_DROP**. Similarly, the number of packets passed to the kernel is displayed via **XDP_PASS**. The **relative drop** represents the percentage of packets dropped relative to the theoretical maximal of dropped packets (represented by **Best-case drop rate**). Calculating the relative drop is done with the following formula: $\text{total dropped packets} / (\text{experiment duration} * \text{invalid traffic rate} - \text{number of ban cycles} * \text{ban limit} * \text{number of malicious clients})$. Each ban cycle lasts for 30 seconds. **Packets received by udp_server** lists the number of packets reaching the application `udp_server`, while **Log messages** represents the number of messages sent via the chosen **IPC** type.

5.5.1 Baseline measurements

For this section, data of 75 experiments have been analyzed.

Using 65,534 clients to send invalid data

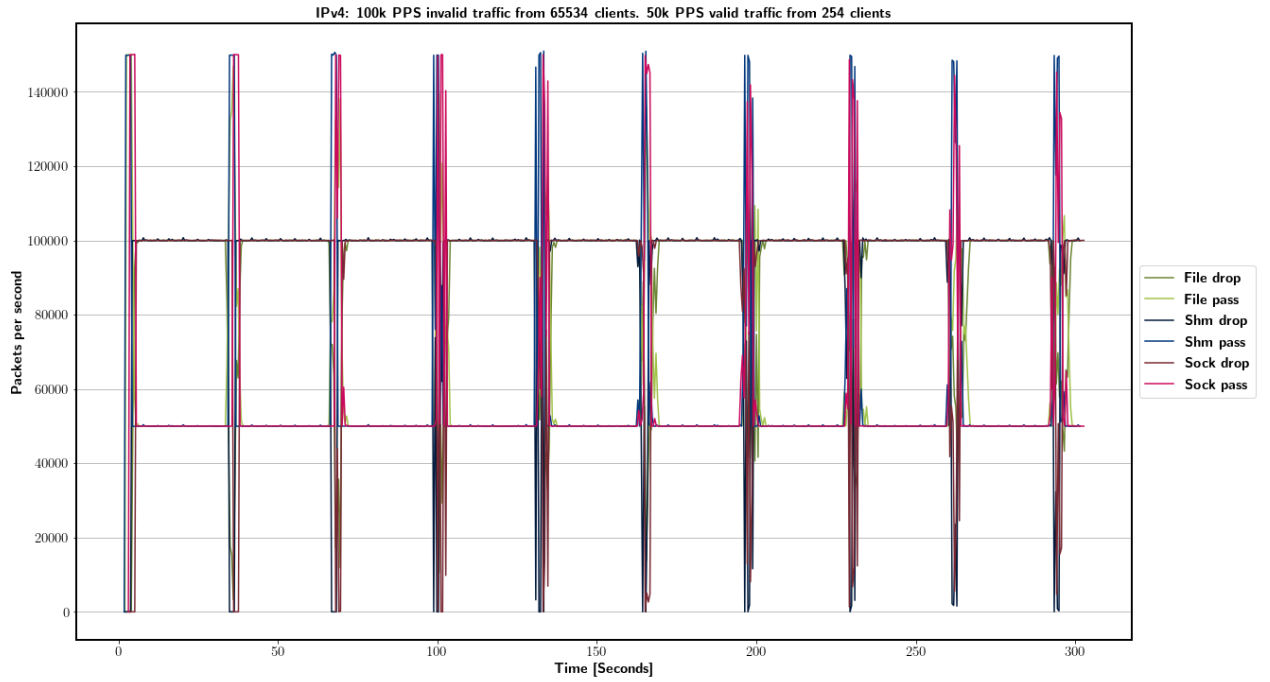
A trend displayed in 5.2 remains prevalent with lower rates of invalid traffic with 65,534 clients sending invalid data: Differences in performance are difficult to spot when graphed. The table in 5.2 does provide more information. All **IPC** types perform similarly well in defending the Denial-of-service (**DoS**) attack.

However, one anomaly stands out. The **relative drop** of the shared memory **IPC** type is over 100%. This happened a total of 21 times over separate measurements, but only when measuring traffic rates of 100k **PPS**. It is suspected that TRex is unable to provide a reliable stream of packets, but only when starting each measurement call. Once a steady stream of packets at desired rates has been established, it does remain stable. Therefore, the number of packets that should be received is higher than the actual incoming traffic rate, resulting in slight inaccuracies when calculating the **relative drop**. While not directly apparent at 100k **PPS** due to slight rounding, this discrepancy can be detected by totaling **XDP_DROP** and **XDP_PASS** up and comparing it to the number of packets that should have theoretically been received. Unfortunately, this issue is present in all data presented in this thesis and depicts a likely flaw in TRex - not the measurements.

Of note is a stark difference in **CPU** time, with a clearly discernible spike when using the socket **IPC** type, likely caused by extensive context-switches between kernel- and

5 Experiments

userspace. All *IPC* types have sent the same number of log messages indicating that, at lower traffic rates, all clients can be banned with the first message they send surpassing the ban limit, regardless of *IPC* type. This claim is supported by the fact that the log messages coincide with the formula: number of ban cycles * ban limit * number of malicious clients; which is the theoretical minimum number of messages needed to successfully ban all clients throughout the duration of the measurement. Otherwise, the results are as expected with the file *IPC* type performing worst due to increased latency.



| IPC type | XDP_DROP [10 ⁶] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 27.84 | 17.16 | 99.29900071 |
| Shm | 28.03 | 16.97 | 100.0000036 |
| Sock | 28.02 | 16.98 | 99.93706566 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 16.81 | 19.66 | 04.95 |
| Shm | 16.97 | 19.66 | 05.94 |
| Sock | 16.96 | 19.66 | 57.90 |

Figure 5.2: Total packets sent: 45m. Best-case drop rate: 93.4466%

In 5.3, the trend of shared memory clearly outperforming other *IPC* types is evident. Again, differences in plotting the number of dropped and passed packets are too small to be visually decipherable and will be omitted until this changes. Instead, a clear difference in performance is once again mainly visible in *CPU* time. The *relative drop* also reveals

that the shared memory **IPC** is performing best, with a lower number of packets being passed to the kernel. An overall drop in performance measured via **relative drop** along all **IPC** types was expected. A generous best-case scenario consists of assuming that all 65,534 clients are banned in the same timespan at all incoming traffic rates. But even then, the inherit latency (even if miniscule) of the Intrusion Prevention System (**IPS**) means that an increase in invalid traffic flow directly correlates with more packets reaching the kernel during each ban cycle. Therefore, the **relative drop** rate must inversely correlate with the invalid traffic rate.

| IPC type | XDP_DROP [10⁸] | XDP_PASS [10⁶] | Relative drop [%] |
|-----------------|----------------------------------|----------------------------------|--------------------------|
| File | 29.40 | 75.07 | 98.05973977 |
| Shm | 29.75 | 37.49 | 99.21848407 |
| Sock | 29.50 | 61.81 | 98.39458207 |

| IPC type | Packets received by udp_server [10⁶] | Log messages [10⁵] | CPU [seconds] |
|-----------------|--------------------------------------------------------|--------------------------------------|----------------------|
| File | 17.51 | 35.10 | 09.69 |
| Shm | 20.02 | 51.93 | 16.86 |
| Sock | 17.13 | 25.52 | 76.00 |

Figure 5.3: Total packets sent: 3,015m. Best-case drop rate: 99.934466%

Even with 30m invalid **PPS**, as seen in 5.4, all **IPC** types successfully defend against the **DoS** attack. The fact that the file **IPC** type outperforms the socket **IPC** type in terms of **relative drop** rate is especially noteworthy. File mode also outperforms shared memory and socket mode on **CPU** usage, which was not expected due to the traditionally high latency of file-based logging approaches. With the high rate of incoming traffic during a ban cycle, the application `udp_server` has to wait on the **IPC** to be able to submit more log messages to `Simplefail2ban`. This results in the system being unable to submit a substantial number of packets to the `udp_server` application. While not explicitly documented in this thesis, these numbers are available in the repository[17]. The difference in packets received by `udp_server` and number of passed packets correlates exactly with this observation. Measuring the number of packets unable to be submitted to `udp_server` was done by checking the file `/proc/net/udp6` on the **DUT**.

A mutual feature of these three measurements is the direct correlation between **relative drop** rate and number of **packets received by udp_server**. Better performing **IPC** types generally receive more packets despite the fact that they block invalid traffic at an increased rate. This is explainable through the inability of the system to supply new packets to `udp_server` while it is still waiting on the **IPC** architecture to deliver data to the **IPS**. **IPC** types with lower latency and higher bandwidth can log more messages during the short influx of packets during each ban cycle. Hence, `udp_server` can receive more packets from the system. These attributes also result in higher **relative drop** rates, thus causing this observation.

Figure 5.5 displays **IPC** types under 30m invalid **PPS** from 65,534 different clients using IPv6 addresses in contrast to the previously used IPv4 addresses. Usage of different **IP** stacks had little impact on the overall results of this thesis, which is why lower traffic rates for IPv6 are omitted.

As expected, the file **IPC** type performed worst, with shared memory performing best.

| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 87.75 | 159.82 | 97.52375345 |
| Shm | 88.30 | 87.23 | 98.13105047 |
| Sock | 87.45 | 139.42 | 97.18179422 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 17.48 | 40.72 | 16.55 |
| Shm | 21.39 | 69.92 | 39.08 |
| Sock | 16.92 | 31.62 | 138.85 |

Figure 5.4: Total packets sent: 9,015m. Best-case drop rate: 99.97815533%

However, contradicting expectations, the socket and shared memory **IPC** types performed better when dealing with IPv6 instead of IPv4 addresses. This is surprising since no changes in general behavior are expected in either `udp_server` or `Simplefail2ban` with one exception: The **Regex** matching feature. In theory, IPv6 banning should be less performant than using IPv4, because IPv6 addresses are longer than IPv4 addresses. Reading these addresses out of the log messages received by `Simplefail2ban` using the **Regex** matching feature should require more time. This idea is supported by the increase in **CPU** time across all **IPC** types compared to figure 5.4 using IPv4. However, an increase in performance can be measured in almost all experiments using IPv6 instead of IPv4. What exactly causes this abnormality is unclear.

| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 87.41 | 211.05 | 97.14091697 |
| Shm | 88.63 | 85.55 | 98.50239609 |
| Sock | 87.77 | 170.03 | 97.54838057 |

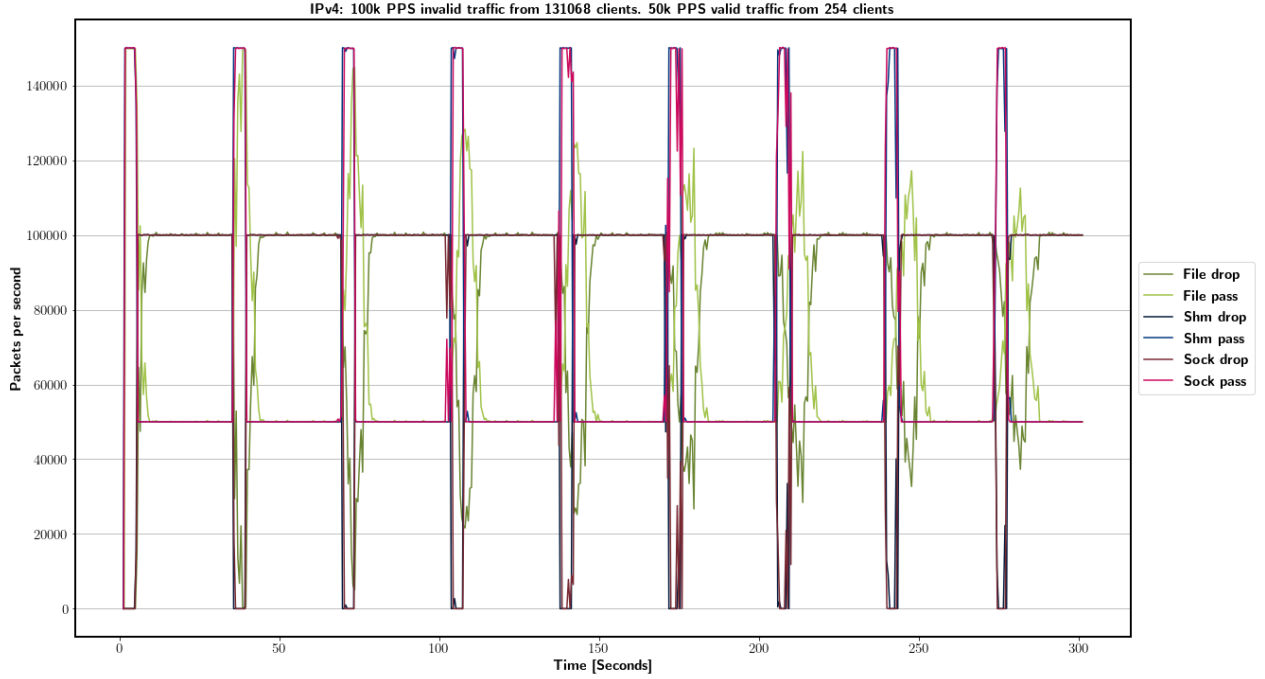
| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 17.20 | 38.73 | 22.51 |
| Shm | 21.79 | 72.38 | 46.03 |
| Sock | 16.92 | 30.04 | 149.69 |

Figure 5.5: Total packets sent: 9,015m. Best-case drop rate: 99.97815533%

Using 131,068 clients to send invalid data

When using 131,068 clients to send invalid data, changes in performance become visible when plotted. Figure 5.6 displays only 100k invalid **PPS**, yet the file **IPC** type struggles to quickly ban all clients. In contrast, both socket and shared memory seem to perform quite similarly across all statistics except for **CPU** time. Here, the socket **IPC** type occupies the **CPU** almost ten times longer than shared memory, again likely due to extensive context-switches between kernel- and userspace.

At invalid traffic rates of 10m **PPS**, displayed in figure 5.7, drastic changes are noticeable. Firstly, shared memory does outperform both the socket and file **IPC** type in **relative drop rate**. Also, the latency of each **IPC** type is clearly visible in the provided graph via their drastically shifted spike of dropped packets each ban cycle. The shared memory **IPC** type both starts and ends its ban cycles before the socket and file **IPC** type. Unexpectedly, the socket **IPC** type still outperforms the file **IPC** type in **relative drop rate**. A general



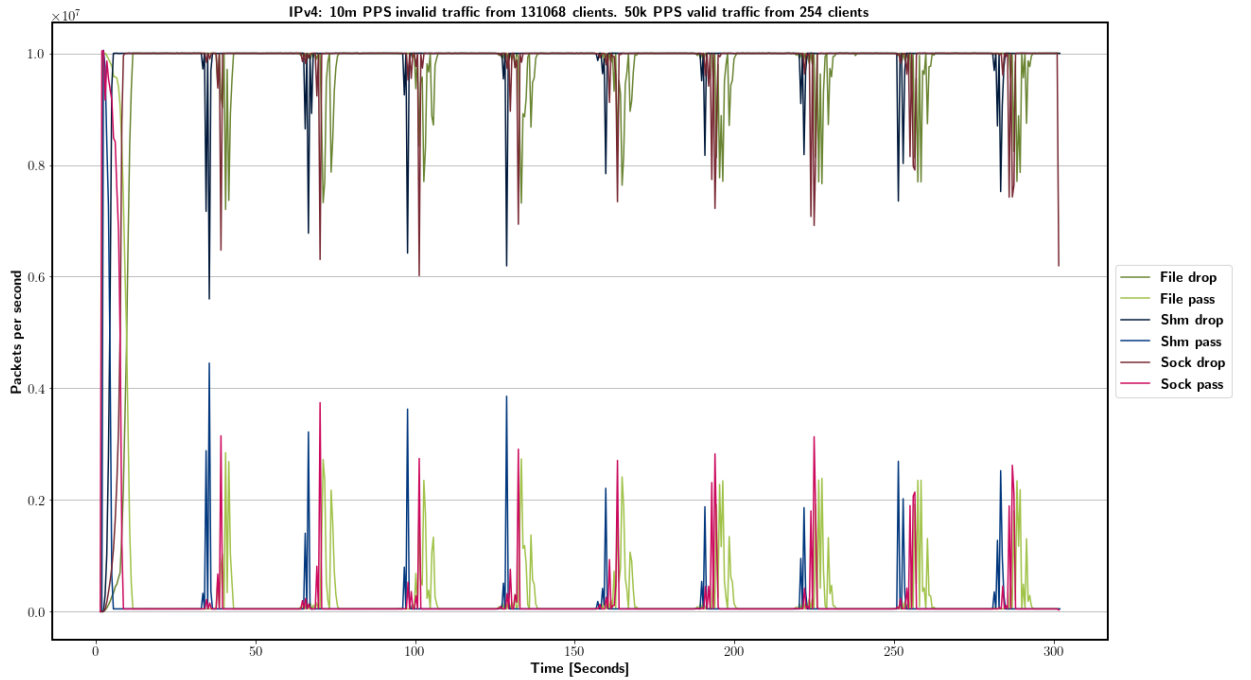
| IPC type | XDP_DROP [10 ⁶] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 25.99 | 19.01 | 99.69409958 |
| Shm | 26.46 | 18.54 | 101.5083842 |
| Sock | 26.44 | 18.56 | 101.4395334 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 18.16 | 35.39 | 08.34 |
| Shm | 18.54 | 35.39 | 10.14 |
| Sock | 18.53 | 35.39 | 100.40 |

Figure 5.6: Total packets sent: 45m. Best-case drop rate: 86.8932%

delay of each ban cycle is visible too. The second to last ban cycle, which should start at 240 seconds, starts late at about 250 seconds. This delay is present in all **IPC** types. It is likely caused by the unbanning thread of Simplefail2ban having to handle 131,068 clients, resulting in them being banned, on average, slightly longer than the intended 30 seconds.

At 30m invalid **PPS**, seen in figure 5.8, the file **IPC** type starts and finishes its ban cycles later than other **IPC** types. While the shared memory and socket **IPC** type start almost simultaneously, sockets require longer to finish a full ban cycle. Differences in **CPU** time are prominent, with the socket **IPC** performing worst and file **IPC** performing best according to the **relative drop rate**. A general trend found in all measurements presented is the low throughput of the socket **IPC** type. Here, it is especially pronounced with the shared memory **IPC** type managing to transmit almost double the amount of **log messages**.



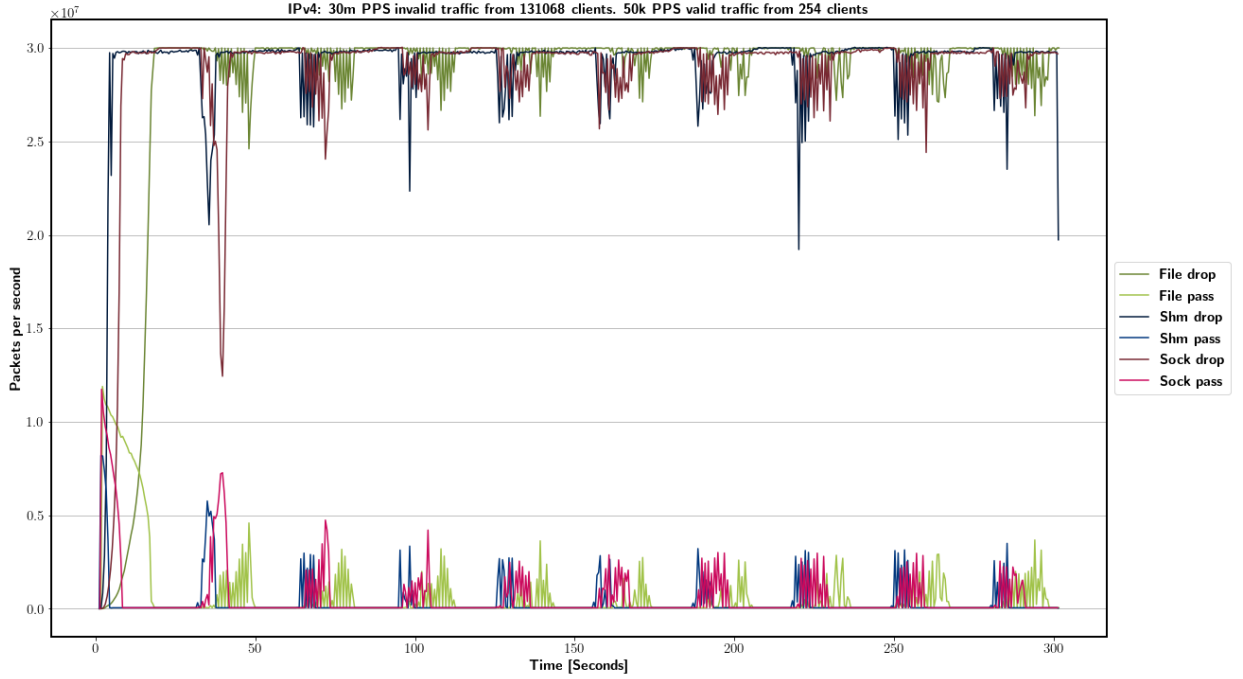
| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 28.77 | 136.15 | 96.03486581 |
| Shm | 29.54 | 58.36 | 98.60515631 |
| Sock | 29.16 | 95.52 | 97.33669129 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 19.31 | 63.90 | 19.39 |
| Shm | 25.40 | 107.54 | 29.47 |
| Sock | 19.02 | 47.67 | 133.54 |

Figure 5.7: Total packets sent: 3,015m. Best-case drop rate: 99.868932%

Switching to IPv6 at a rate of 30m invalid **PPS** does not yield any fundamentally different results: 5.9. Again, performance of all **IPC** types improves slightly, still with no known cause. Shared memory performs best, with the file **IPC** type performing worst. The direct correlation between **relative drop rate** and **packets received by udp_server** is also still present.

When using a mixed **IP** stack, two streams of invalid data were configured in TRex: One being IPv4, the other being IPv6. Both streams were producing exactly 50% of the invalid traffic and consisted out of 65,534 clients each. Naturally, no single client sent both IPv4 and IPv6 packets. The most expressive measurement is displayed in 5.10 with 30m invalid **PPS**. Expectations were that the **relative drop rate** for all **IPC** types would land firmly between the equivalent measurements using IPv4 and IPv6. However, this is not



| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 85.02 | 238.30 | 94.51036756 |
| Shm | 87.57 | 104.14 | 97.33826458 |
| Sock | 86.12 | 180.89 | 95.73084169 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 18.04 | 74.39 | 38.99 |
| Shm | 25.32 | 115.04 | 71.92 |
| Sock | 18.33 | 59.26 | 323.02 |

Figure 5.8: Total packets sent: 9,015m. Best-case drop rate: 99.95631067%

| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 85.73 | 228.07 | 95.29278185 |
| Shm | 87.60 | 109.08 | 97.37706621 |
| Sock | 86.21 | 177.33 | 95.82614459 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 17.90 | 69.14 | 38.41 |
| Shm | 25.08 | 111.45 | 74.71 |
| Sock | 18.67 | 61.84 | 317.37 |

Figure 5.9: Total packets sent: 9,015m. Best-case drop rate: 99.95631067%

the case. The figure 5.10 does not display this property. In fact, no other measurements using a mixed IP stack definitively exhibit this property. Here, in figure 5.10, the shared memory and socket IPC types outperform the measurement utilizing pure IPv6 displayed in 5.9. Though, most measurements still outperform their pure IPv4 counterpart at a minimum. But performance regarding their pure IPv6 counterpart is not definitive, the variance between measurements is too severe.

| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| File | 85.12 | 286.15 | 94.61335186 |
| Shm | 88.02 | 105.83 | 97.84149307 |
| Sock | 86.30 | 212.81 | 95.93428297 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| File | 17.69 | 70.65 | 47.15 |
| Shm | 25.13 | 111.62 | 94.64 |
| Sock | 18.00 | 59.85 | 353.34 |

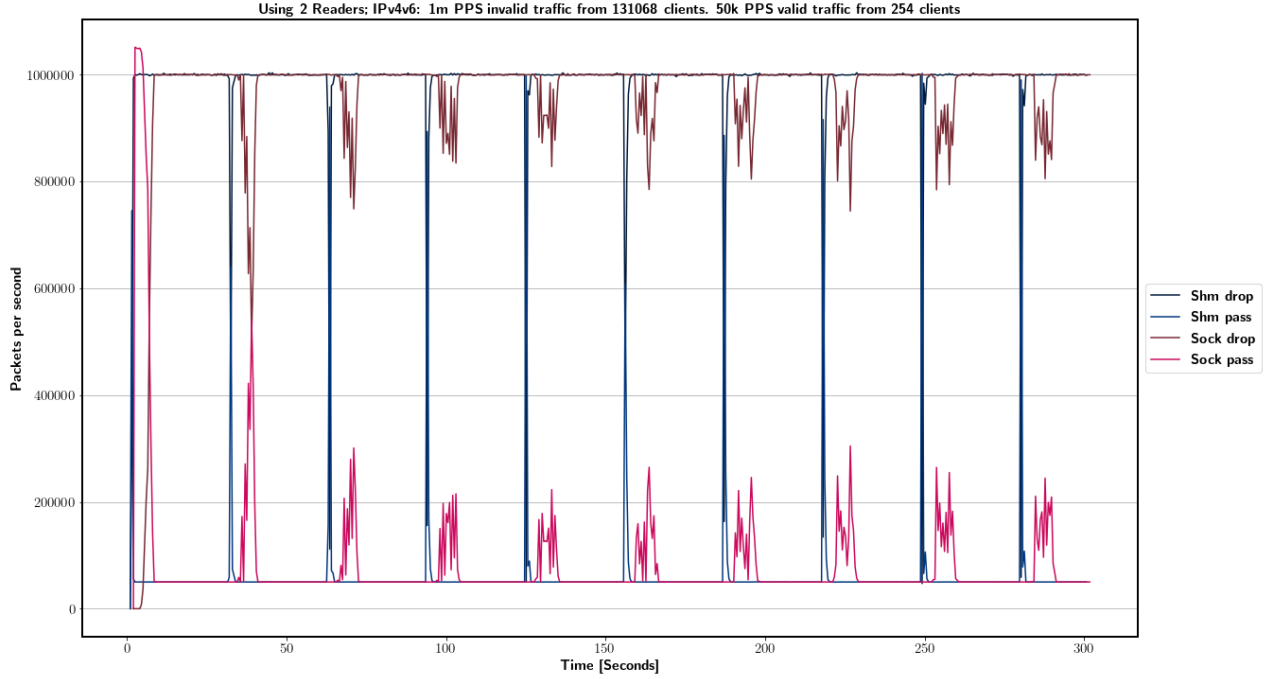
Figure 5.10: Total packets sent: 9,015m. Best-case drop rate: 99.95631067%

5.5.2 2nd reader measurements

Initially, data of 10 experiments have been analyzed for this section. At 100k invalid PPS, performance of both the shared memory and socket IPC types was almost identical. The only exception is the CPU time in which the socket IPC performed up to six times worse than shared memory. The results become interesting when increasing invalid traffic rate to 1m PPS, as seen in figure 5.11. The graph displays a clear delay between the ban cycles of the shared memory and socket IPC types. Still, both modes are able to supply both the IPS Simplefail2ban and a slower reader process with data while defending against the DoS attack. Again, CPU time of the socket IPC type is significantly higher than its shared memory counterpart. The relative drop rate is also worse by about 2 percent (equal to 6,3M more packets reaching the kernel over the duration of the measurement, or 21,000 PPS), with fewer messages logged.

Figure 5.12 shows data measured with 20m invalid PPS. The socket IPC type struggles to supply both the IPS and the second reader with log messages, having logged less data than the shared memory IPC type. The graph also displays this inability to keep up with incoming traffic during the first two ban cycles. While shared memory was able to fully ban all malicious clients in just one 30 second ban cycle, the socket mode is not. Given enough time, the socket IPC type is able to recover and successfully defend against the DoS attack.

That changes in figure 5.13. Now, the socket IPC type is unable to defend against the DoS attack, and the system is overwhelmed - failing to drop all invalid traffic. The relative drop falls to approximately 54 percent, the number of messages passed to the kernel rises significantly and the application udp_server is not able to handle the influx of incoming data. Fewer log messages are sent to all readers and the CPU time falls, likely due to the system not having any resources left for user space applications. Meanwhile, the shared memory IPC type performs just as well as in figure 5.10, when no second reader



| IPC type | XDP_DROP [10 ⁷] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| Shm | 29.53 | 19.75 | 99.72283593 |
| Sock | 28.91 | 25.94 | 97.6334018 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| Shm | 19.48 | 44.91 | 17.76 |
| Sock | 18.29 | 41.47 | 80.82 |

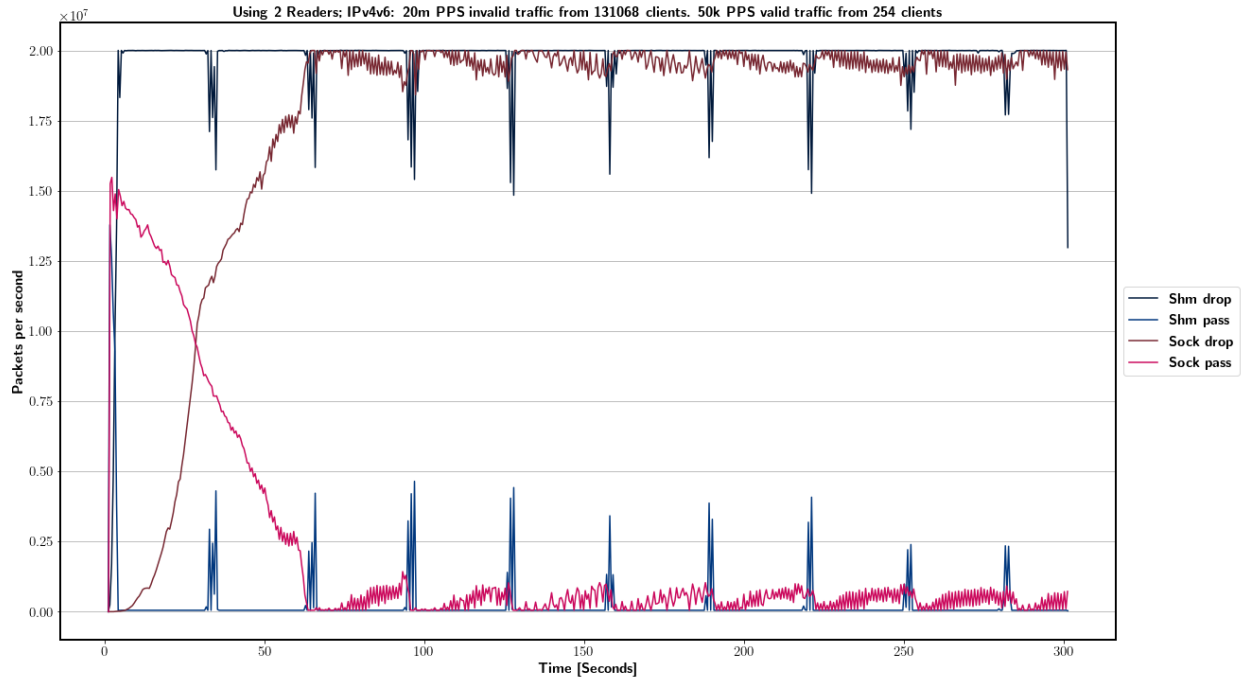
Figure 5.11: Total packets sent: 315m. Best-case drop rate: 98.68932%

was attached to the [IPC](#) architecture.

A difference of this scale was not initially expected. However, increased performance of the shared memory [IPC](#) type was attributed to the overwrite feature. Enabling this feature meant that slower reader processes were ignored if they slowed down any writers. The socket [IPC](#) type cannot abandon slow readers, it has to wait for each reader to receive all data, unlike the shared memory [IPC](#).

Another experiment was conducted to confirm the link between enabling the overwrite feature and the increased performance of the shared memory [IPC](#) type: The shared memory [IPC](#) type is used without having the overwrite feature enabled. Expectations were, that having to wait for all reader processes to receive data would result in a performance decrease. This measurement is displayed in figure 5.14.

No such decrease in performance was measured whatsoever. The only logical conclusion

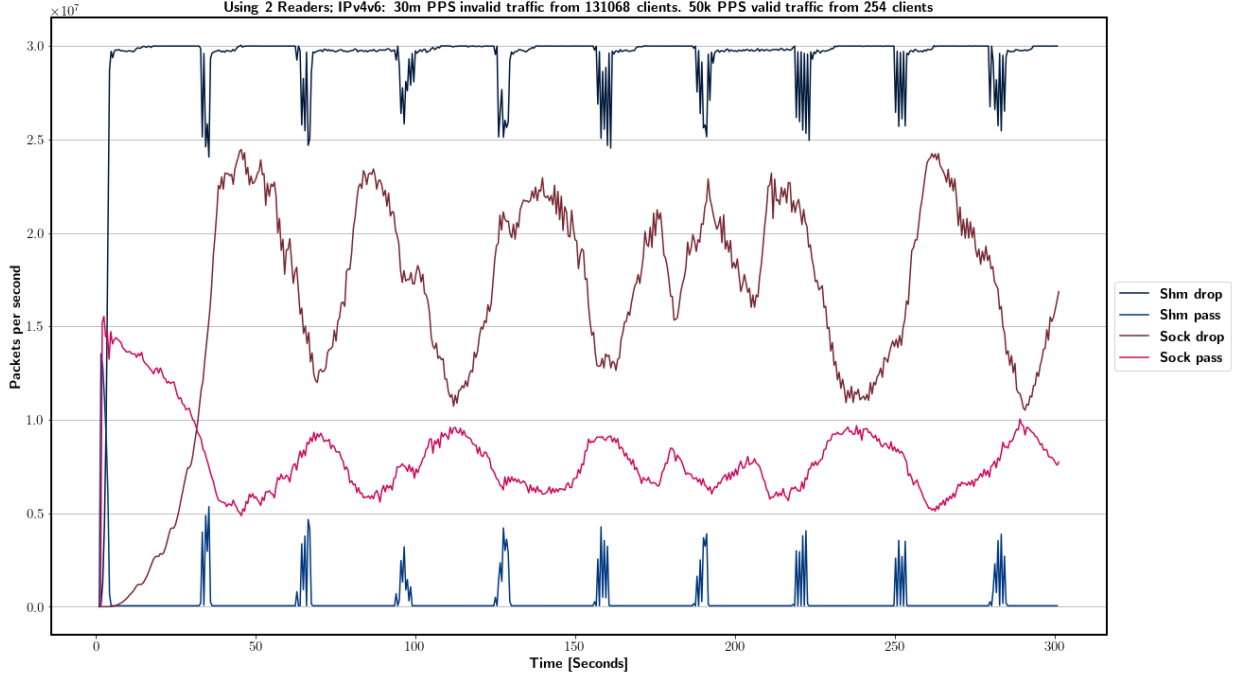


| IPC type | XDP_DROP [10^8] | XDP_PASS [10^6] | Relative drop [%] |
|----------|---------------------|---------------------|-------------------|
| Shm | 59.15 | 79.92 | 98.64873119 |
| Sock | 52.45 | 624.81 | 87.47139407 |

| IPC type | Packets received by udp_server [10^6] | Log messages [10^5] | CPU [seconds] |
|----------|-------------------------------------------|-------------------------|---------------|
| Shm | 24.61 | 101.26 | 49.90 |
| Sock | 11.32 | 65.01 | 251.49 |

Figure 5.12: Total packets sent: 6,015m. Best-case drop rate: 99.934466%

is, that the shared memory `IPC` type manages to supply multiple readers with faster data transfer than is required for even 30m incoming invalid PPS. The overwrite feature was not needed and had no real impact on performance. Increased latency when using the socket `IPC` type likely culminated to such a degree that supplying multiple readers with data was not feasible.



| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| Shm | 87.83 | 118.74 | 97.63360872 |
| Sock | 48.80 | 2385.53 | 54.22323337 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| Shm | 24.70 | 108.17 | 94.60 |
| Sock | 3.10 | 30.04 | 31.91 |

Figure 5.13: Total packets sent: 9,015m. Best-case drop rate: 99.95631067%

| IPC type | XDP_DROP [10 ⁸] | XDP_PASS [10 ⁶] | Relative drop [%] |
|----------|-----------------------------|-----------------------------|-------------------|
| Shm | 87.99 | 125.56 | 97.81321365 |
| Sock | 48.80 | 2385.53 | 54.22323337 |

| IPC type | Packets received by udp_server [10 ⁶] | Log messages [10 ⁵] | CPU [seconds] |
|----------|---------------------------------------------------|---------------------------------|---------------|
| Shm | 24.95 | 108.43 | 99.47 |
| Sock | 3.10 | 30.04 | 31.91 |

Figure 5.14: Total packets sent: 9,015m. Best-case drop rate: 99.95631067%

6 Conclusion & Outlook

In this thesis, the previously developed light-weight Intrusion Prevention System (IPS) Simplefail2ban and its selection of Inter-process communication (IPC) was expanded to include UNIX domain sockets. With it being the first kernel-based IPC available, thorough measurements were conducted to evaluate its performance to the already implemented shared memory and file-base IPC modes. Expectations were that UNIX domain sockets would not outperform shared memory, because of a constant need for context-switches between kernel- and userspace. This initial hypothesis turned out to be true. The socket IPC type was beat in all analyzed metrics (number of unwanted requests dropped, number of log messages sent and Central Processing Unit (CPU) time) by the shared memory mode of Simplefail2ban. However, performance of the UNIX domain socket mode was still well up to the task. It remained competitive in experiments utilizing only one process to receive data, performing only around 2 percent worse than its shared memory counterpart. During less intense traffic flow, this small disadvantage in performance shrunk even further. Data indicates that latency in the socket IPC type was at least on par with the shared memory mode. Rather, a lack of bandwidth and increased drain on system resources are the main causes identified for the observed decrease in performance. Conversely, UNIX domain socket did consistently outperform the file-based IPC, albeit by a small fraction: regularly being less than one percentage point in relative drop rate. Overall, the socket IPC type was always able to block over 95,5 percent (and 98,5 percent on average) of all incoming traffic, therefore defending against Denial-of-service (DoS) attacks successfully.

While never being an explicitly desired feature, the socket IPC type does provide the option to attach, up to a pre-defined maximum, and detach a varying number of both writer and reader processes during runtime. In contrast, the shared memory IPC only provides the option to attach multiple reader processes. This allows for, in theory, flexible reusing of the socket IPC architecture for other applications. Regrettably however, usage of UNIX domain sockets in scenarios with multiple reader processes is not recommended due to a lack of bandwidth, resulting in the socket IPC performing significantly worse than the shared memory IPC. At a rate of 20m invalid Packets per second (PPS), defending against a DoS attack in a single ban cycle was unfeasible when employing UNIX domain sockets. Yet, after multiple ban cycles, Simplefail2ban was able to recover and repel the incoming DoS attack. With 30m invalid PPS, a recovery became impossible. The shared memory IPC type was able to keep its performance up even when supplying a second reader process, and disabling the overwrite feature.

Potential improvements of the socket IPC should focus on increasing the bandwidth. This makes it possible to react more efficiently and effectively in the event of a sudden influx of messages, primarily occurring at the beginning of a ban cycle or DoS attack. Furthermore, no explicit authorization of reader processes exists in the current implementation. As a result, any process can attach to the socket IPC architecture, which may pose

a security concern.

Overall, this thesis proved that the kernel-based UNIX domain sockets remain a viable option as [IPC](#) coming reasonably close to, yet unable to surpass the higher performance of the shared memory [IPC](#) type. Continued development could focus on the possibility of scaling the socket [IPC](#) beyond the local system by employing internet sockets. Providing an improved high-level Application Programming Interface ([API](#)) for easier integrability with established real-world applications, such as `syslog` or `journald`, is also worthwhile investigating.

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A Abbreviations

| | |
|----------------|----------------------------------------|
| IDSs | Intrusion Detection Systems |
| HIPS | Host-based Intrusion Prevention System |
| HIDS | Host-based Intrusion Detection System |
| IDS | Intrusion Detection System |
| IPS | Intrusion Prevention System |
| Regex | Regular Expression |
| TCP | Transmission Control Protocol |
| IP | Internet Protocol |
| eBPF | extended Berkeley Packet Filter |
| XDP | eXpress Data Path |
| IPC | Inter-process communication |
| UDP | User Datagram Protocol |
| DPDK | Data Plane Development Kit |
| CPU | Central Processing Unit |
| PMDs | Poll Mode Drivers |
| ACK | Acknowledgment |
| TCP-SYN | Synchronize/Acknowledge |
| DoS | Denial-of-service |
| API | Application Programming Interface |
| ID | Identification |
| DUT | Device under Test |
| GNU | GNU's Not Unix |
| NIC | Network Interface Card |
| PPS | Packets per second |

B Source Files

The source files and corresponding repository can be accessed here: https://gitup.uni-potsdam.de/fips/fips_sock. For project access, please contact either me or the second supervisor, Max Schrötter.

Bibliography

- [1] *Fail2ban GitHub*. <https://github.com/fail2ban/fail2ban/wiki/How-fail2ban-works>. Last visited on 28-07-2024. 2017 (cit. on pp. 1, 4).
- [2] Florian Mikolajczak. "Implementation and Evaluation of an Intrusion Prevention System Leveraging eBPF on the Basis of Fail2Ban". MA thesis. University of Potsdam, 2022 (cit. on pp. 1, 4, 5, 20).
- [3] Paul Raatschen. *Design and Implementation of a new Inter-Process Communication Architecture for Log-based HIDS for 100 GbE Environments*. Bachelorthesis. 2023 (cit. on pp. 1, 5, 6, 8–10, 17, 18, 20).
- [4] James P. Anderson. "Computer Security Threat Monitoring and Surveillance". In: *James P. Anderson Company* (1980) (cit. on p. 3).
- [5] Dorothy E. Denning. "An Intrusion-Detection Model". In: *IEEE Transactions on Software Engineering* SE-13.2 (1987) (cit. on p. 3).
- [6] Letou Kopelo, Devi Dhruwajita, and Y. Jayanta Singh. "Host-based Intrusion Detection and Prevention System (HIDPS)". In: *International Journal of Computer Applications* 69.(0975 - 8887) (2013) (cit. on p. 4).
- [7] Linux man-pages project. *Socket*. <https://man7.org/linux/man-pages/man2/socket.2.html>. Last visited on 09-07-2024. 2024 (cit. on p. 7).
- [8] Brian "Beej Jorgensen" Hall. *Beej's Guide to Network Programming: Using Internet Sockets*. 2023 (cit. on p. 7).
- [9] Linux man-pages project. *Unix Domain Socket*. <https://man7.org/linux/man-pages/man7/unix.7.html>. Last visited on 09-07-2024. 2024 (cit. on pp. 7, 10).
- [10] Cisco Systems. *Official TRex Website*. <https://trex-tgn.cisco.com/>. Last visited on 09-07-2024 (cit. on p. 8).
- [11] The Linux Foundation. *Official DPDK Website*. <https://www.dpdk.org/>. Last visited on 09-07-2024 (cit. on p. 8).
- [12] *Official Scapy Website*. <https://scapy.net/>. Last visited on 16-07-2024 (cit. on p. 8).
- [13] IEEE Computer Society and The Open Group. *IEEE P1003.1™, Draft 3*. Tech. rep. 2007 (cit. on p. 10).
- [14] Linux man-pages project. *Iovec*. <https://man7.org/linux/man-pages/man3/iovec.3type.html>. Last visited on 11-07-2024. 2024 (cit. on p. 14).
- [15] Linux man-pages project. *Select*. <https://man7.org/linux/man-pages/man2/select.2.html>. Last visited on 12-07-2024. 2024 (cit. on p. 16).

- [16] Raj Jain. *The Art of Computer Systems Performance Analysis: Techniques For Experimental Design, Measurement, Simulation, and Modeling*, NY: Wiley. John Wiley & Sons, Inc., 1991 (cit. on p. 17).
- [17] Daniel Aeneas von Rauchhaupt. *Thesis Git Repository*. https://gitup.uni-potsdam.de/fips/fips_sock. Repository containing all source code and measurement data. 2024 (cit. on pp. 23, 25).